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AIR-BEARING SPIN FACILITY FOR MEASURING ENERGY DISSIPATION

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16. Abstract

The air-bearing spin facility was developed to determine experimentally the effect of energy dissipation upon the motion of spinning spacecraft. The facility consists of an air-bearing spin table, a telemetry system, a command system, and a ground control station. The air-bearing spin table was designed to operate in a vacuum chamber, specifically the Dynamic Test Chamber (DTC) located in the Test and Evaluation (T&E) Division, Goddard Space Flight Center (GSFC). Tests were run on spacecraft components such as fuel tanks, nutation dampers, reaction wheels, and active nutation damper systems. Each of these items affected the attitude of a spinning spacecraft. An experimental approach to determine these effects was required because the dissipation of these components could not be adequately analyzed. The results of these experiments have been used, with excellent results, to predict spacecraft motion.

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AIR-BEARING SPIN FACILITY FOR MEASURING ENERGY DISSIPATION

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INTRODUCTION

During the analysis and design of their attitude control systems (ACS), the earliest spacecraft were considered rigid bodies. Because of this, spacecraft such as Explorer-1, TACSAT-1, and Applications Technology Satellite-5 (ATS-5) have experienced severe limit cycles or have lost attitude control due to unexpected energy dissipation. Friction forces in the bearings of motors and the viscous forces in the sloshing of fluids in a spinning spacecraft can contribute to stability problems. If a spinning spacecraft is in an unstable configuration (spin moment of inertia is less than the transverse moment of inertia), the excess energy dissipation can cause the spacecraft to go into a flat spin. Many spacecraft incur this problem in the early stages of a mission during transfer from one orbit to another.

Designers of spacecraft control systems must consider the energy dissipation of components such as moving mechanisms (rotating or oscillating) and fluid sloshing (fuel, damper fluid, and heat pipe fluid). The complexity of these mechanisms prevents their being fully analyzed during design, therefore, data must be obtained experimentally.

With these considerations in mind, objectives were developed and performance goals were defined for tests to be conducted on the air-bearing spin facility. The three main objectives of the tests are to:

- Compare flight data to simulator data,
- Predict energy dissipation effects of flight components,
- Develop new, improved component and flight system designs.

The goals for overall performance of the air-bearing spin facility are to provide:

- Simplicity and safety of operation,
- Mass properties equivalent to the spacecraft,
- High-spin speed to minimize the effects of gravity,
- Low air drag,

- A statically and dynamically balanced spinning structure,
- Low-energy dissipation in the spinning structure,
- A large range of values of inertia and inertia ratio,
- The following degrees of freedom: spin axis—continuous, and transverse axes—±12° half-cone angle,
- That equipment under test could be mounted on the table as on the spacecraft,
- Accurate measurements of table angular position, velocity, and acceleration,
- Data output suitable for analysis.

AIR-BEARING SPIN FACILITY

The facility consists of three major parts: an air-bearing spin table, vacuum chamber support equipment, and a ground station. For testing, the spin table (figure 1) and the support equipment are located inside the Dynamic Test Chamber (DTC) in the Test and Evaluation (T&E) Division at Goddard Space Flight Center (GSFC). A ground station is located outside the DTC near the chamber wall feedthrough (figure 2).

Spin Table

The air-bearing spin table is a welded tubular aluminum (6061-T6) structure with aluminum honeycomb decks. The electronic equipment, weights, and the equipment to be tested are mounted on the table. The table is rigidly attached to a 25.4-cm (10-in.) spherical beryllium ball that acts as one-half of an air bearing. The other half is a mated brass cup mounted on a stand. High-pressure nitrogen [5.0×10^5 Pa (75 psi)] is supplied through lines in the stand to 33 orifices in the cup. The ball and table are floated on the nitrogen film between the ball and cup. The table has complete freedom to rotate about the vertical axis and is permitted ± 12° rotation from the horizontal axis.

The component to be tested is mounted on the table in an appropriate location and the table inertias are then scaled to represent the spacecraft. The table is balanced with the center of mass at the center of rotation of the spherical air bearing. A torque-free spacecraft is thus represented by the table.

A computer program was designed to determine mass properties of the air-bearing table, as well as to locate equipment on the table to obtain the desired balance, spin, and transverse inertias.

Spin-table Instrumentation

Instrumentation includes two linear accelerometers for measuring nutation and a gyro for determining spin rate. Two stationary optical trackers monitor table motion (figure 3)—one located to the north and the other to the west of the table. The trackers optically

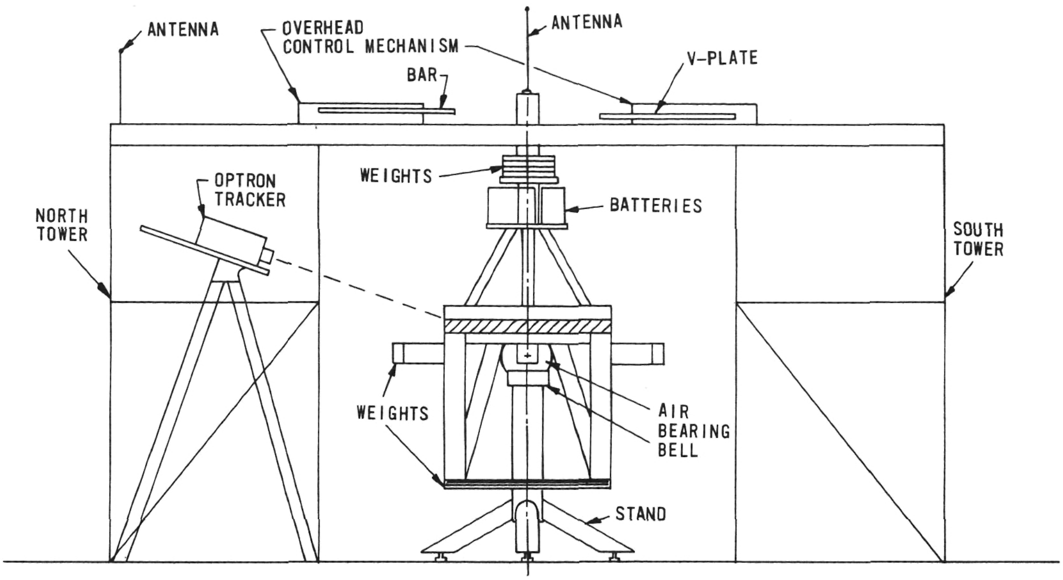

Figure 1. Air-bearing spin table.

Figure 2. Ground station outside vacuum chamber.

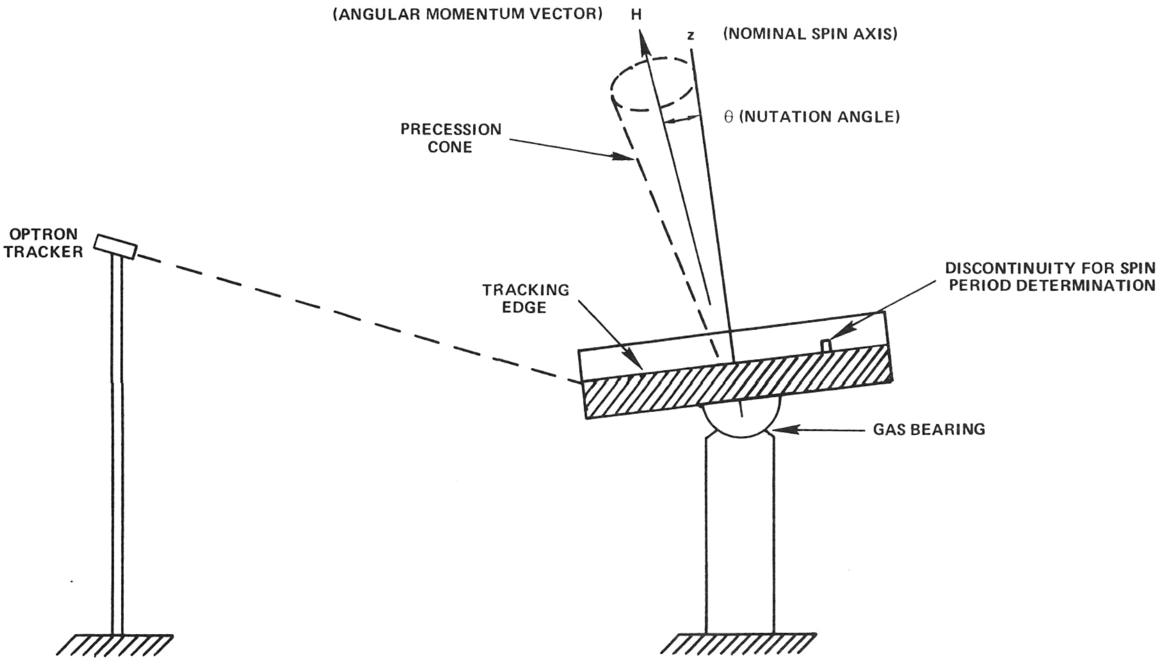

Figure 3. Optron attitude sensing.

follow the motion of a black-and-white target mounted on the table to monitor spin-axis deviation from vertical. Two television cameras monitor table motion. One camera is located in the top of the vacuum chamber looking down on the table and the other, a side-mounted camera, monitors the action of the spin-up and capture mechanisms on the stand. Either television camera output can be recorded on a video tape recorder (VTR). A telemetry system with six channels sends information from the table, and a five-channel system is used to command systems on the table. Batteries on the table provide +28 Vdc at 12 Ah and +5 Vdc at 4 Ah for onboard systems.

OPERATING PROCEDURE

To run a test, the table is floated. A mechanism on the stand positions the table vertically and spins up the table. These operations are controlled from the ground station. To reduce the effects of air drag, the table is operated in a vacuum chamber (DTC) at a pressure of 1.3 Pa (1×10^{-2} mm Hg). The table, stand, and overhead mechanism are controlled from consoles outside the chamber.

When the table is up to speed, the spin-up mechanism is retracted, and the table is allowed to spin and move freely on the air bearing. The spin-axis motion is monitored by instrumentation on and off the table. A component with a moving part (mechanical or fluid) that is placed under test will have an effect upon the motion of the spin axis through the dynamics of the system.

When sufficient data are taken, the spinning nutating body must be captured. This is accomplished by the overhead mechanism and by the spin mechanism on the stand.

The system is capable of speeds up to 130 rpm. Inertia ratios (spin inertia/transverse inertia) have varied from 0.14 to 1.25. Spin inertias have ranged from 13.5 to 135 kg-m^2 (10 to 100 slug-ft^2). The values of the inertia ratios and spin inertia are dependent upon the mass of the equipment to be tested and the equipment location on the table.

TEST EQUIPMENT AND TESTS

Test Equipment

The following is a list of test equipment that can be found in the three major areas:

- Air-bearing Spin-table Equipment

  Optron target (angular position)
  Rate gyro (spin rate)
  Accelerometer (body-fixed nutation)
  Command receiver
  Telemetry transmitter
  Batteries
  Nutation inducer (small reaction wheel)
  Remote control balance weights (3)
  Pneumatic system (tanks, regulators, and jets)

- Vacuum Chamber Support Equipment

  Air-bearing stand
  Towers for overhead control mechanism
  Overhead control mechanism
  Optron optical scanners
  Television cameras
  Telemetry and command antennas
  Pneumatic and control cables

- Ground Station Equipment

  Stand and overhead mechanism control box
  Pneumatic controls for floating table
  Telemetry receiver
  Command transmitter
  Optron electronic units
  Nutation inducer control
  Two-channel strip chart recorders
  Tape recorder for telemetry
  Television monitor
  Television recorder/player

Power supplies
Clock
Digital data logger

Tests

Four categories of tests have been run on the air-bearing spin table: (1) fuel slosh, (2) dampers, (3) reaction wheels, and (4) active nutation dampers. All tests were run in the DTC at a pressure 1.3 Pa (1 $\times$ 10^{-2} mm Hg).

Fuel Slosh

For the Synchronous Meteorological Satellite (SMS) fuel-slosh test, four spherical plastic tanks were used. The inside diameter, 29.8 cm (12 in.), of these plastic tanks was the same as the flight tanks. For safety, water was used as the fluid, since it has approximately the same viscosity as hydrazine. Clear plastic tanks were used so that the action of the water could be observed. The tanks were mounted in an aluminum ring which fits around the table. The ring was mounted on the table in three different positions: (1) the center of gravity (CG), (2) one foot below CG, and (3) two feet below CG. Weights on the side of each tank were removed or added when the fill ratio was changed, to maintain balance and inertia ratio. The parameters that were changed during the test were spin speed, fill ratio, tank location, and inertia ratio.

An aluminum engineering model of the UK-5 tank was tested on the air-bearing spin table. The tank was cylindrical in shape with hemispheric ends, 41.9 cm (16.5 in.) high, and 17.8 cm (7 in.) in diameter. The tank was mounted on the upper platform of the spin table along the spin axis. For safety reasons, acetone, which has approximately the same viscosity as propane, was used as the fluid in the tank.

A Geodetic Earth Orbiting Satellite (GEOS) fuel-slosh test was run for the European Space Research Organization (ESRO). Two conosphere tanks with 35-cm (13.75-in.) inside diameter were mounted in a ring around the table. The ring was mounted around the table 26.7 cm (10.5 in.) below CG. Different fill ratios were used with water as the fluid and different parameters tested were fill ratio, spin speed, and inertia ratio.

A Meteosat satellite fuel-slosh test was also run for ESRO. Three spherical tanks of 29.2-cm (12.25-in.) inside diameter were tested. The fluid was water. The tanks were mounted in a ring around the table. This ring was mounted in two positions, 22.4 cm (8.8 in.) and 75.2 cm (29.6 in.) below CG. The parameters varied were tank position, fill ratio, spin speed, and inertia ratio.

For the International Sun Earth Explorer-C (ISEE-C) satellite fuel-slosh test, the GEOS conosphere tanks were used. The ring containing the two tanks was mounted 26.7 cm (10.5 in.) below CG. Only one inertia ratio of 0.80 and tank position were tested. Parameters varied were fill ratio and spin speed.

The GP-A fuel-slosh test was run for the Marshall Space Flight Center (MSFC). The tank, which is an ammonia boiler, was supplied by MSFC. For safety reasons, petroleum ether was used as the fluid instead of ammonia. The L-shaped aluminum tank had 15 internal baffles. A fan and a battery were also tested. The only parameter varied was fill ratio.

Table 1 presents the test data for the fuel-slosh tests. Figures 4 through 7 illustrate the GEOS fuel-slosh tests on the spin balance machine (figure 4), on the inertia machine (figure 5), and in vacuum chambers (figures 6 and 7).

Table 1
Fuel-slosh Tests

Satellite	Tank Material	No. of Tanks	Inside Dimension (cm)	Location		Spin Inertia ($kg\text{-}m^2$)	Inertia Ratio Transverse/ Spin	Fill Ratio
				Horiz Dist. from Vert. Axis (cm)	Vert Dist. from CG (cm)			
SMS	Sphere,	4	29.8	53.4	0	52.8	0.38	0
	plastic		dia.					0.375
					-30.9	47.4	0.61	0.5
								0.625
					-60.9	32.5	0.63	0.88
UK-5	Cylinder,	1	17.8 dia X	0	34.3	12.7	0.2	1.00
	aluminum		41.9 high			43.4	1.05	0.85
GEOS	Conosphere,	2	35.0 dia.	58.4	-26.7	61.7	0.35	0.55
	plastic							0.60
						58.8	0.40	0.65
								0.70
						56.9	0.46	
Meteosat	Sphere,	3	29.2 dia.	67.8	-22.4	73.9	0.35	0.50
	plastic				-75.2	76.6	0.36	0.65
						79.3	0.37	0.35
						84.7	0.39	
ISEE-C	Conosphere,	2	35.0 dia.	58.4	-26.7	78.6	0.80	0.55
	plastic							0.60
								0.65
								0.70
GP-A	L-shaped	1	31.8 X	38.1	-42.4	20	0.14	0
	aluminum		17.8 X					0.60
			10.2					0.80
								1.00

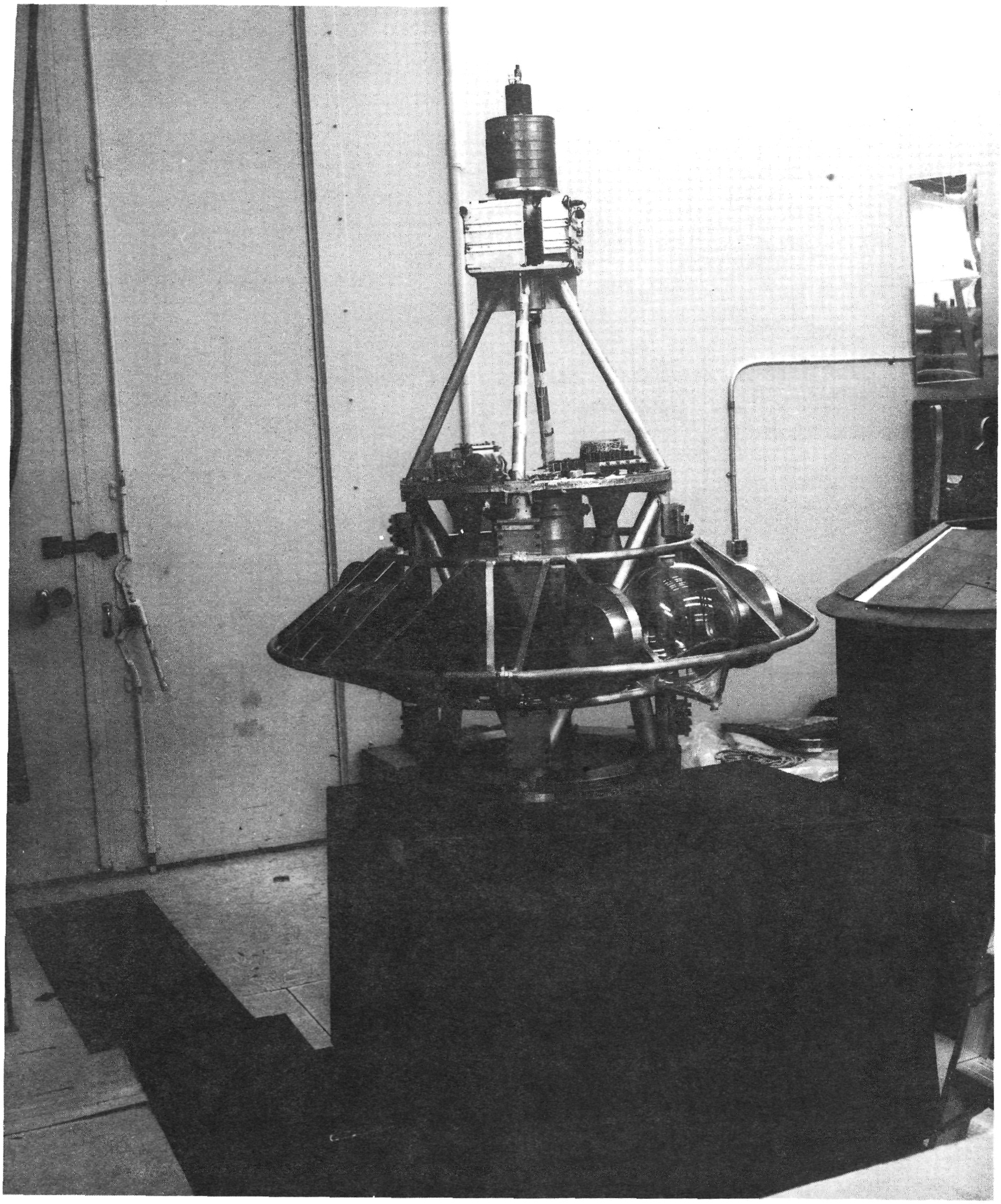

Figure 4. GEOS fuel-slosh test on spin balance machine.

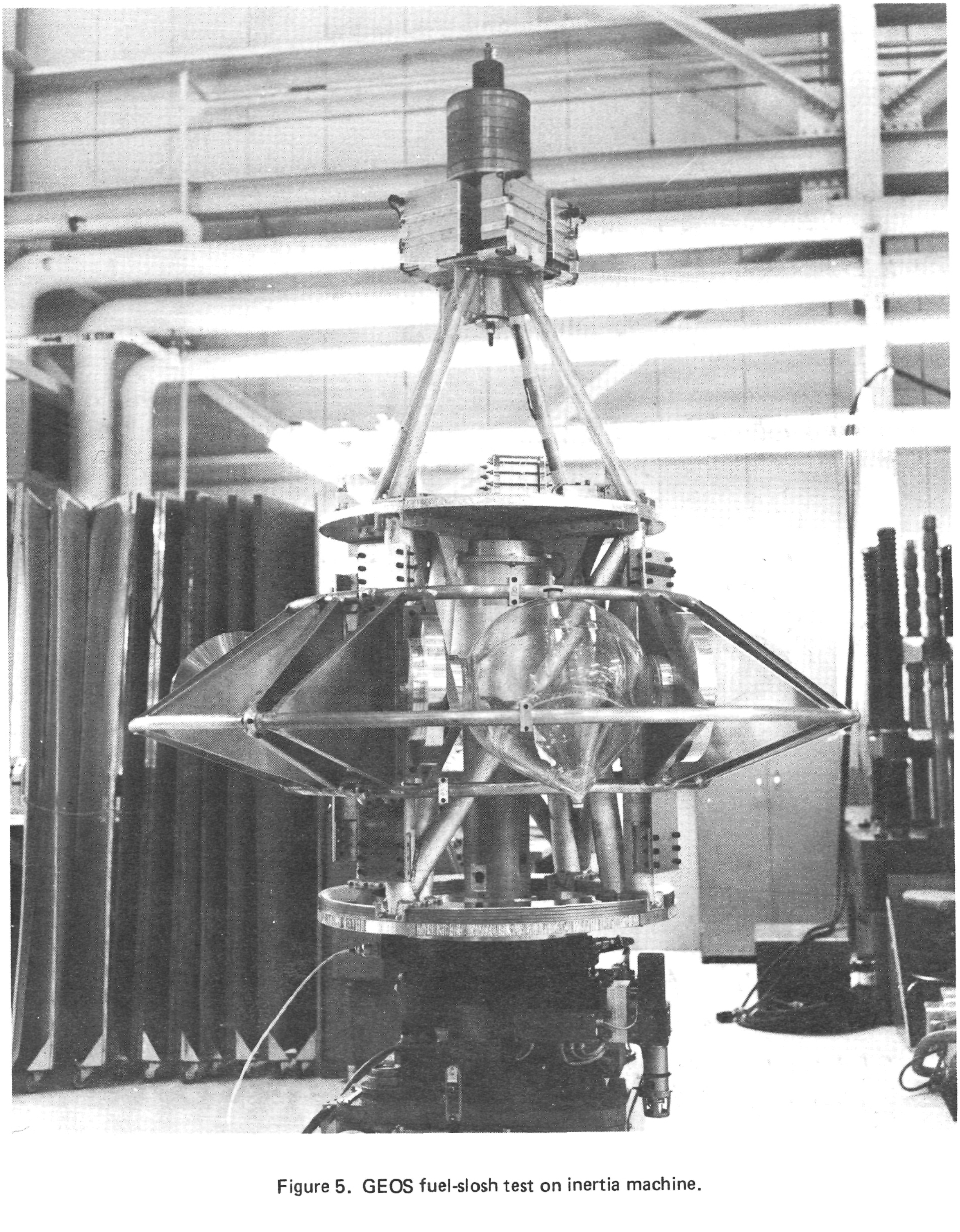

Figure 5. GEOS fuel-slosh test on inertia machine.

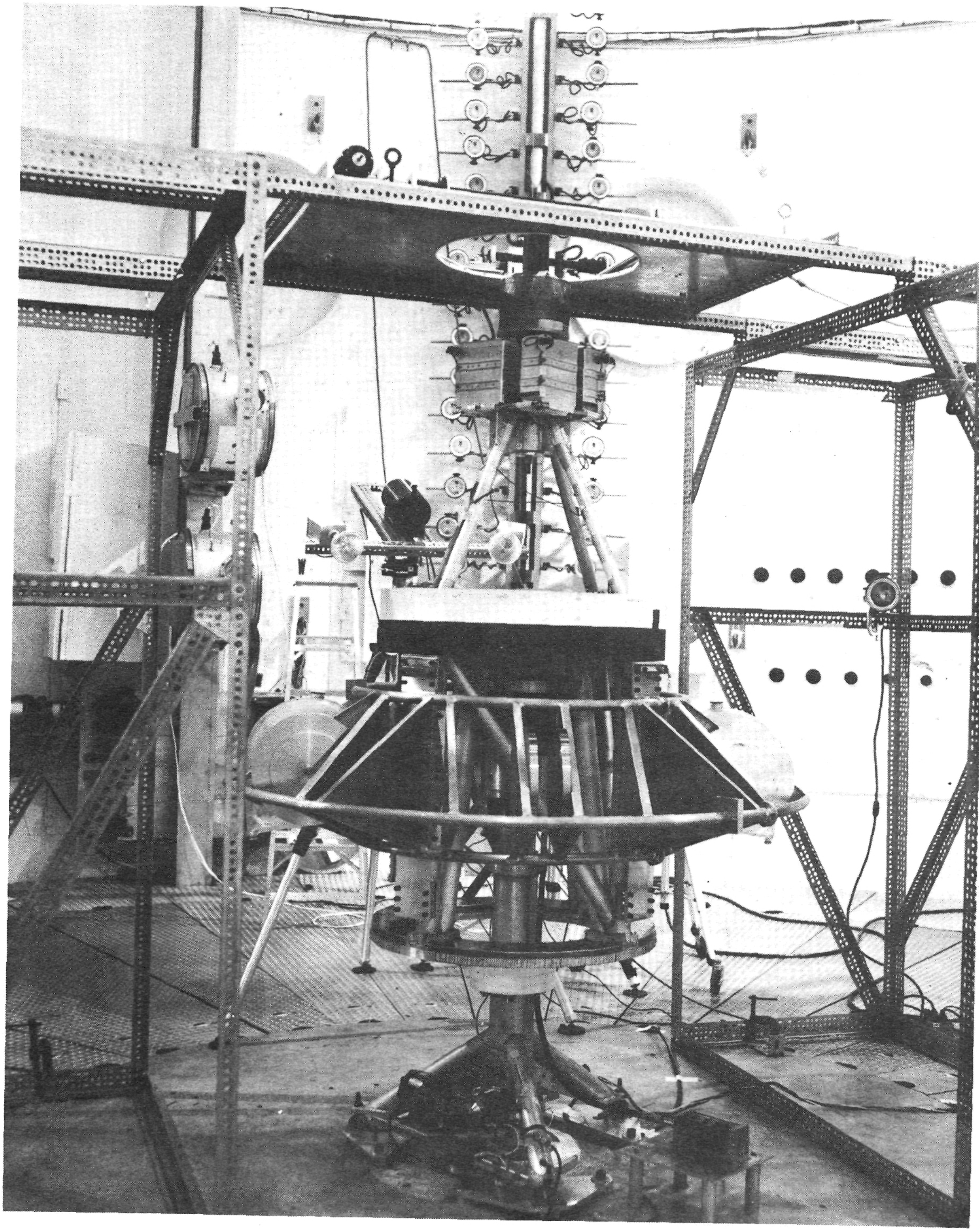

Figure 6. GEOS fuel-slosh test in vacuum chamber.

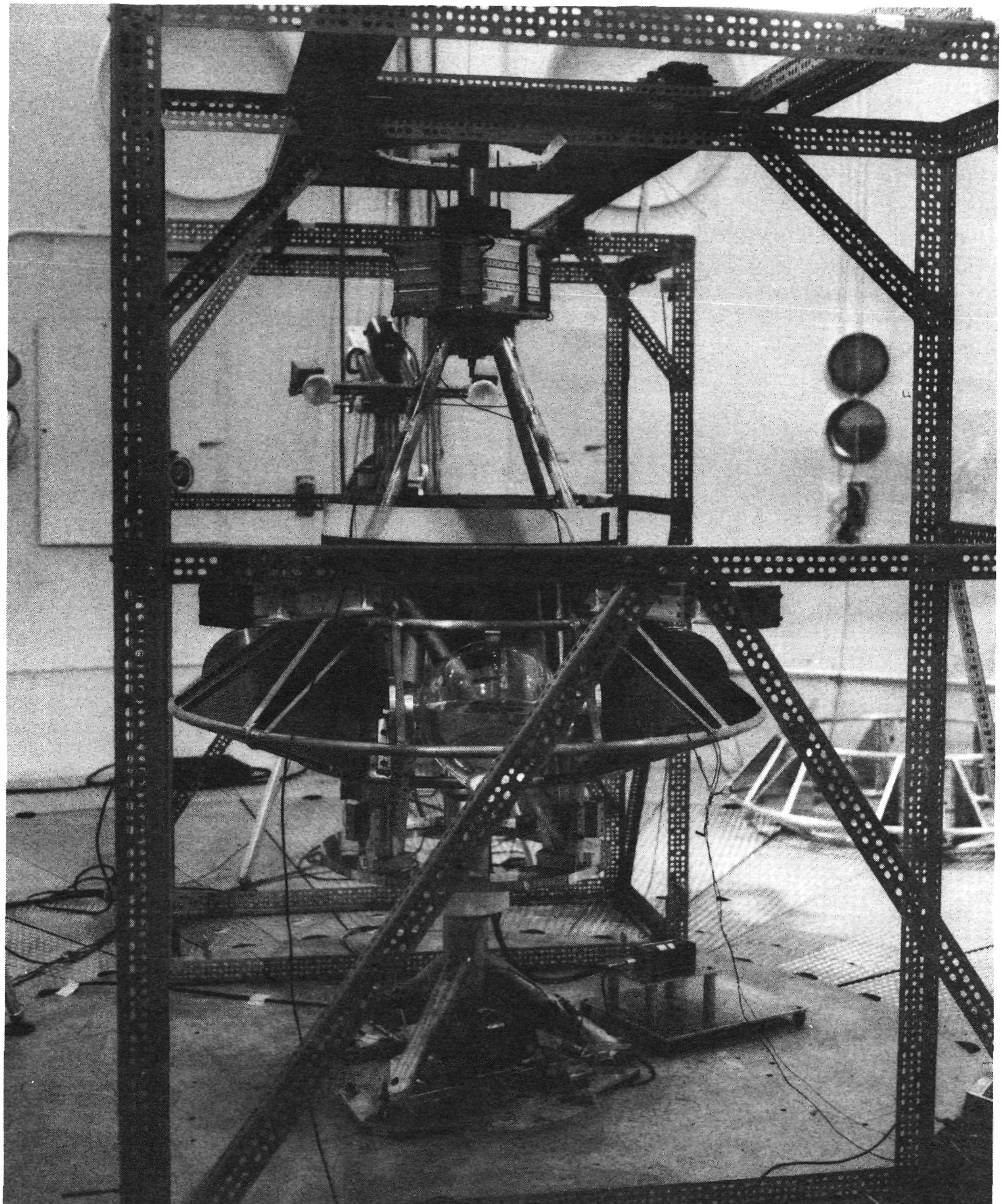

Figure 7. GEOS fuel-slosh test in vacuum chamber.

Dampers

Engineering models of dampers have been tested for the Helios, UK-5, Radio Astronomy Explorer-B (RAE-B), Improved TIROS Operational Satellite (ITOS), and Meteosat satellites. The dampers have fluid in their tubes, and the motion of this fluid dissipates the nutation energy of a spinning spacecraft. Two types of dampers were tested—the ring damper and the parallel tubes. The fluids in the dampers were either mercury or silicon oil. The dampers were mounted on the table in a position similar to that on the spacecraft. The parallel tube dampers were slanted so the fluid was in the proper position at 100 rpm. The inertia ratio was made the same as the satellites represented, and if possible, the spin inertia was made the same; if not possible, it was scaled.

Table 2 presents the damper test data. Figures 8 and 9 show the Meteosat damper in the vacuum chamber.

Table 2
Damper Tests

Satellite	Type, Material, Fluid	Qty	Size (cm)	Location: Horiz Dist. from Vert Axis (cm)	Location: Vert Dist. from CG (cm)	Spin Inertia (kg-m²)	Inertia Ratio Transverse/ Spin
Helios	Ring, fiberglass, mercury	1	58.9 dia.	0	22.8 76.2	24 39 110 114	0.39 0.60 1.05 1.14
UK-5	Parallel tube, aluminum	2	51.6 long	43.1	0 -34.3	9.5 110 114 118	0.20 1.05 1.15 1.25
RAE-B	Ring, aluminum, silicon oil	1	45.7 X 60.9	45.7	-12.7	39	0.60
ITOS	Ring, aluminum, silicon oil	2	91.4 X 91.4	60.9	-35.6	88	0.80
Meteosat	Parallel tube, aluminum	1	20.3 long	109.2	-55.9	50 61 52	0.42 0.78 0.71

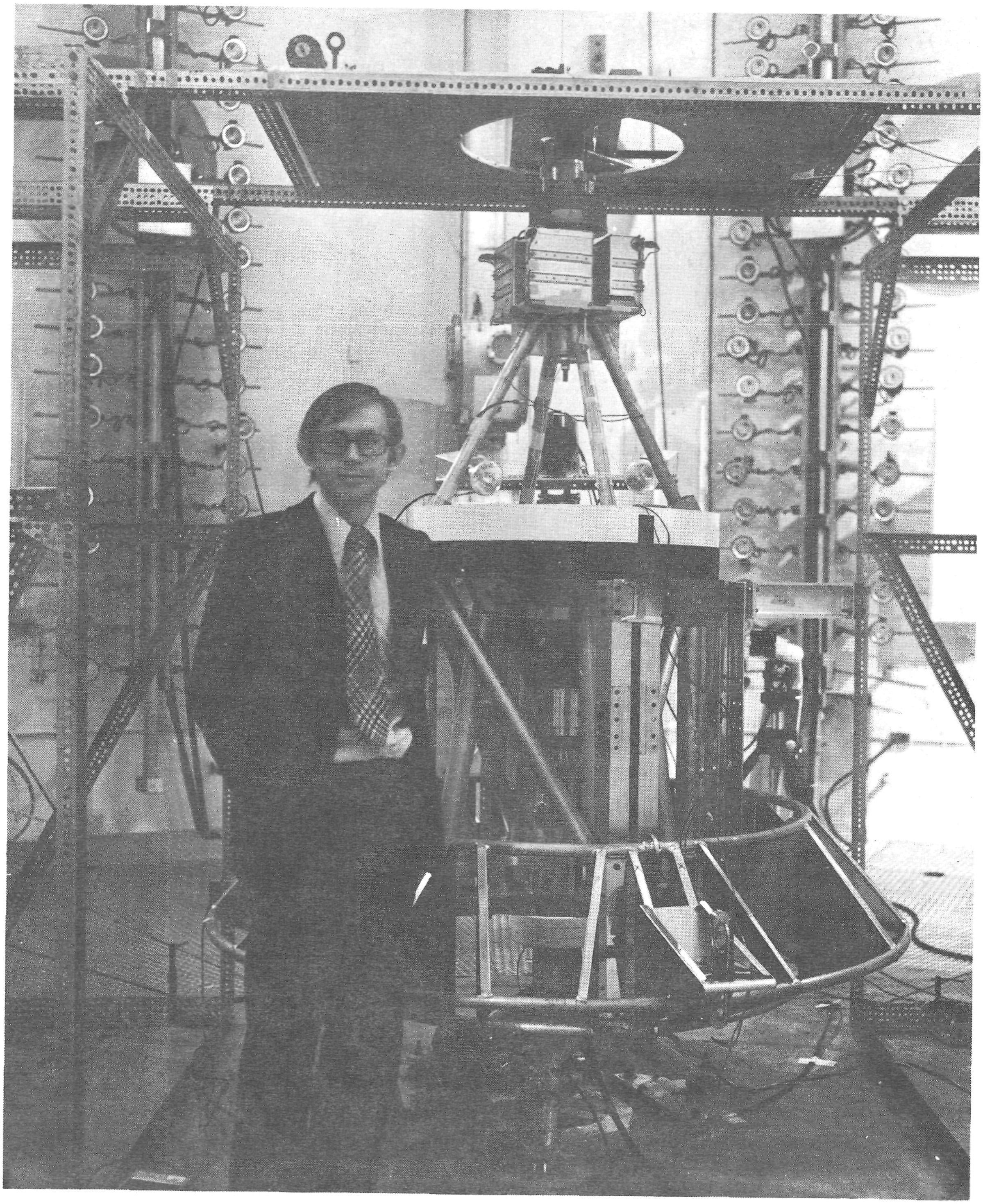

Figure 8. Meteosat damper in vacuum chamber.

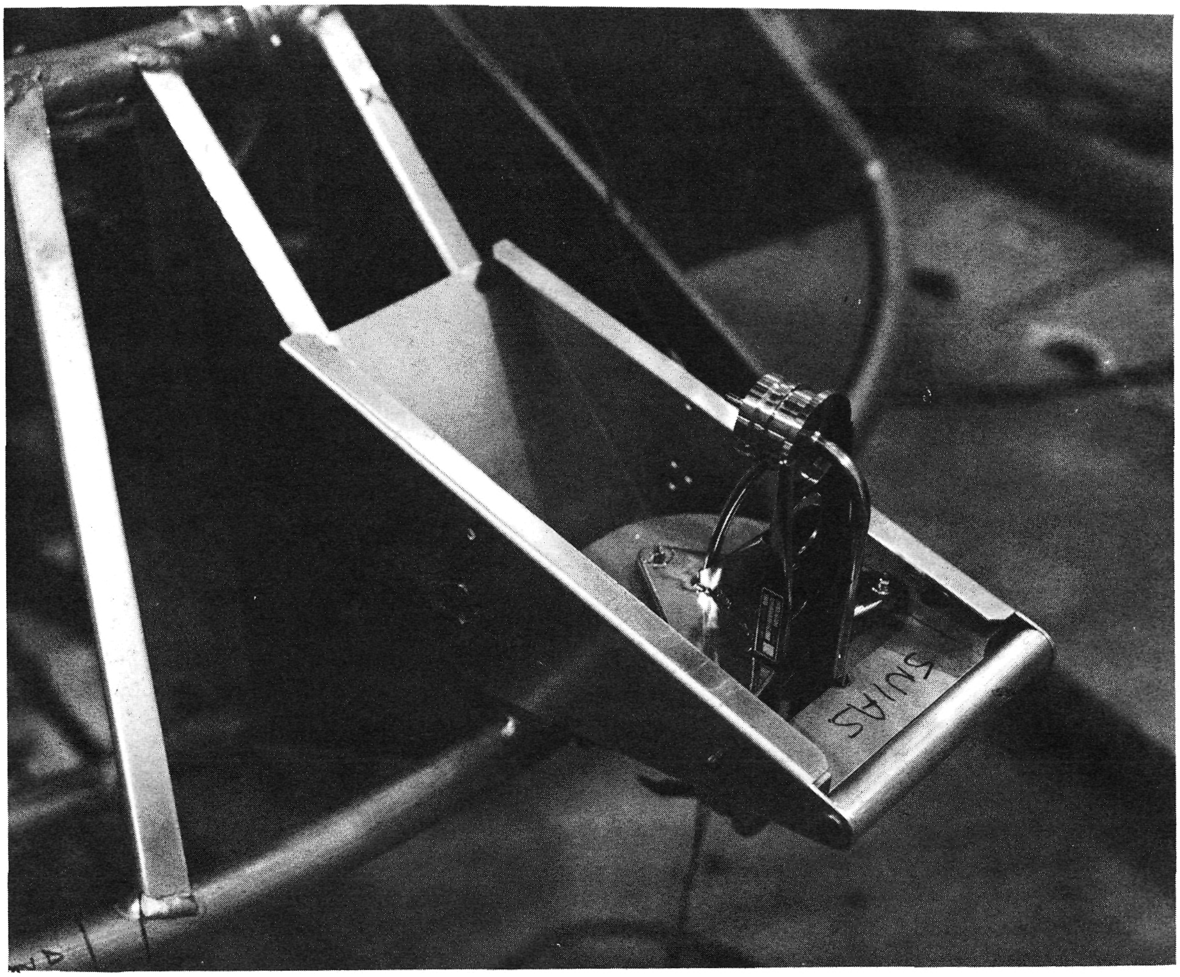

Figure 9. Meteosat damper in vacuum chamber (close up).

Reaction Wheels

Engineering models of reaction wheels have been tested for the Small Astronomy Satellite-B (SAS-B), ITOS, and Atmosphere Explorer (AE) satellites. The reaction wheels were mounted on the upper platform of the air-bearing table with their axes concentric with that of the table. The vertical distance from the table CG to the center of the reaction wheel was made the same as the satellites. The wheel control electronics were also mounted on the table. The wheel and table were rotated at the same speed as the satellite.

The SAS-B reaction wheel was tested with no conclusive results. It is believed that the small size of the wheel, 1.36 kg (3 lb), compared to that of the table, 227 kg (500 lb), did not affect the attitude of the table.

The ITOS reaction wheel [9.1 kg (20 lb)] (figures 10 and 11) and the AE wheel [13.6 kg (30 lb)] (figure 12) were tested with excellent results. The nutation problems encountered in flight were duplicated. Different bearings were tested to observe their influence upon

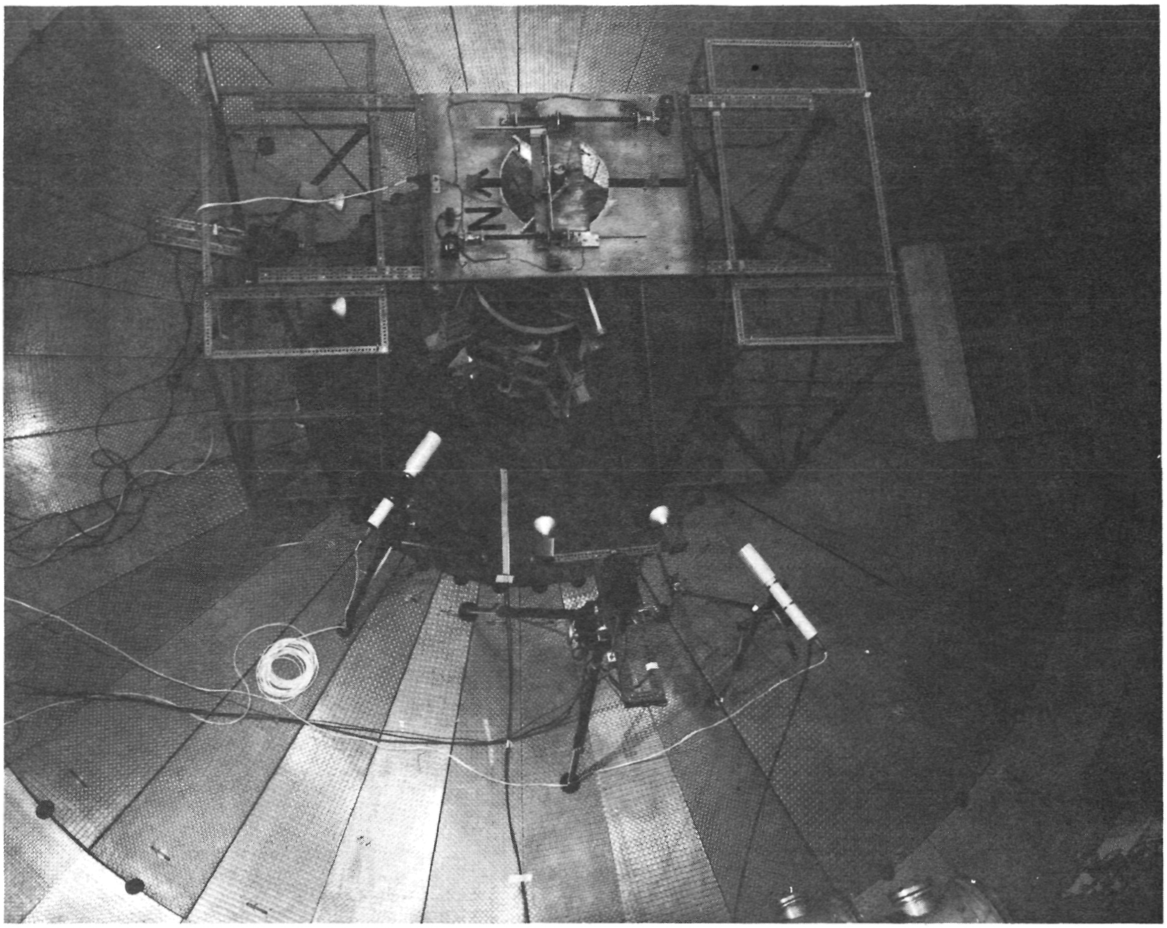

Figure 10. ITOS reaction wheel in vacuum chamber (top view).

nutation. Because of the lower table speed required for wheel testing, a remote control, fine balancing system was added to the table. A finer balance was achieved with this method.

Table 3 presents the data for the reaction-wheel tests.

Active Nutation Dampers

An active nutation damper control system, designed for the SMS satellite, was tested on the air-bearing table (figure 13). The system consisted of an accelerometer, electronics control box, and pneumatic jets. To detect table nutation, the accelerometer was mounted on an arm with its sensitive axis vertical. The electronics control box was mounted on the upper platform in the center of the table. The pneumatic package consisted of two high-pressure nitrogen tanks, two regulators, and two thrusters. The tanks were mounted opposite each other on a center line through the air-bearing ball. This was done so that when gas was expelled, weight was lost from the center of the ball or the CG of the table. This location would not affect the balance of the table during the test. The regulators used

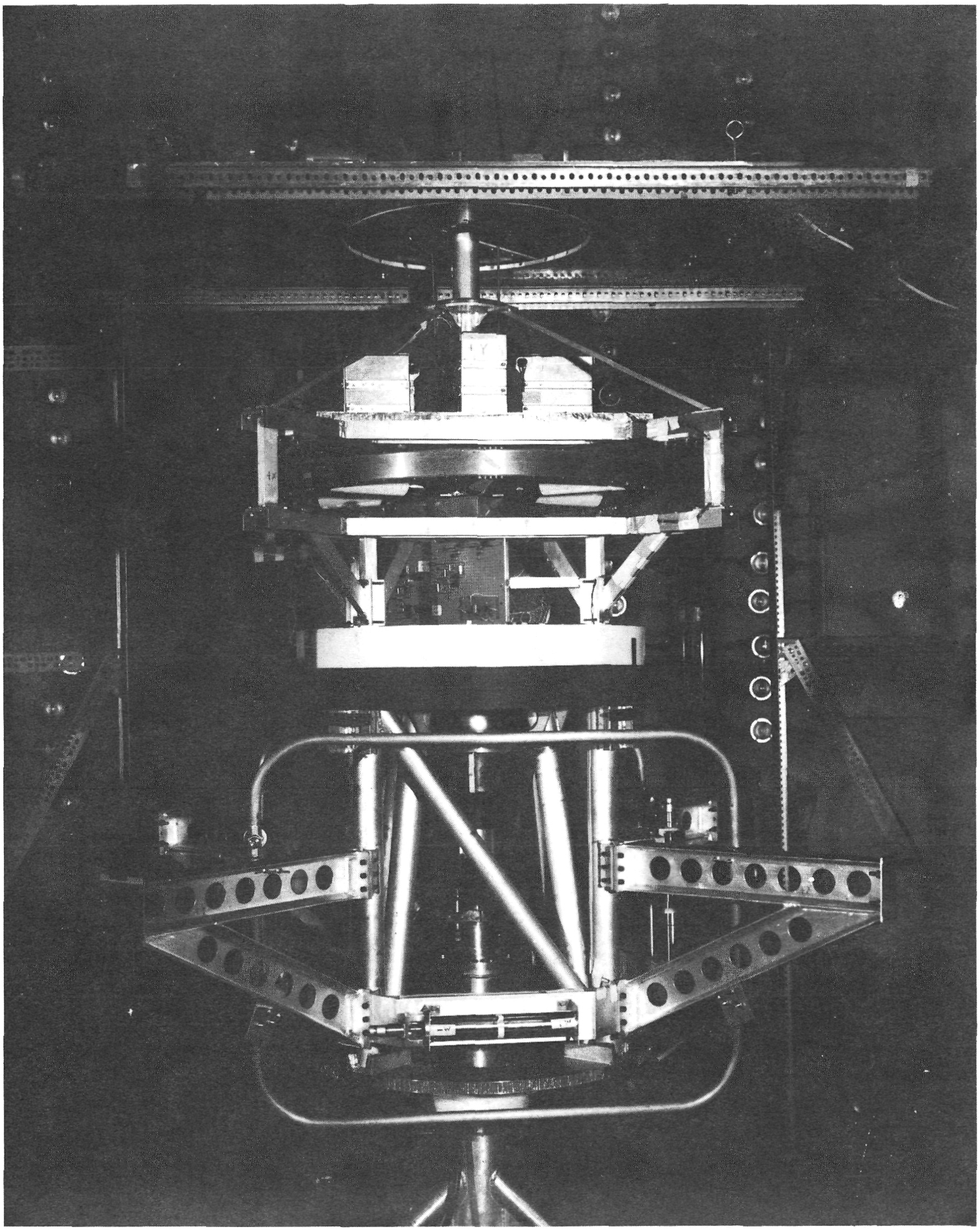

Figure 11. ITOS reaction wheel in vacuum chamber.

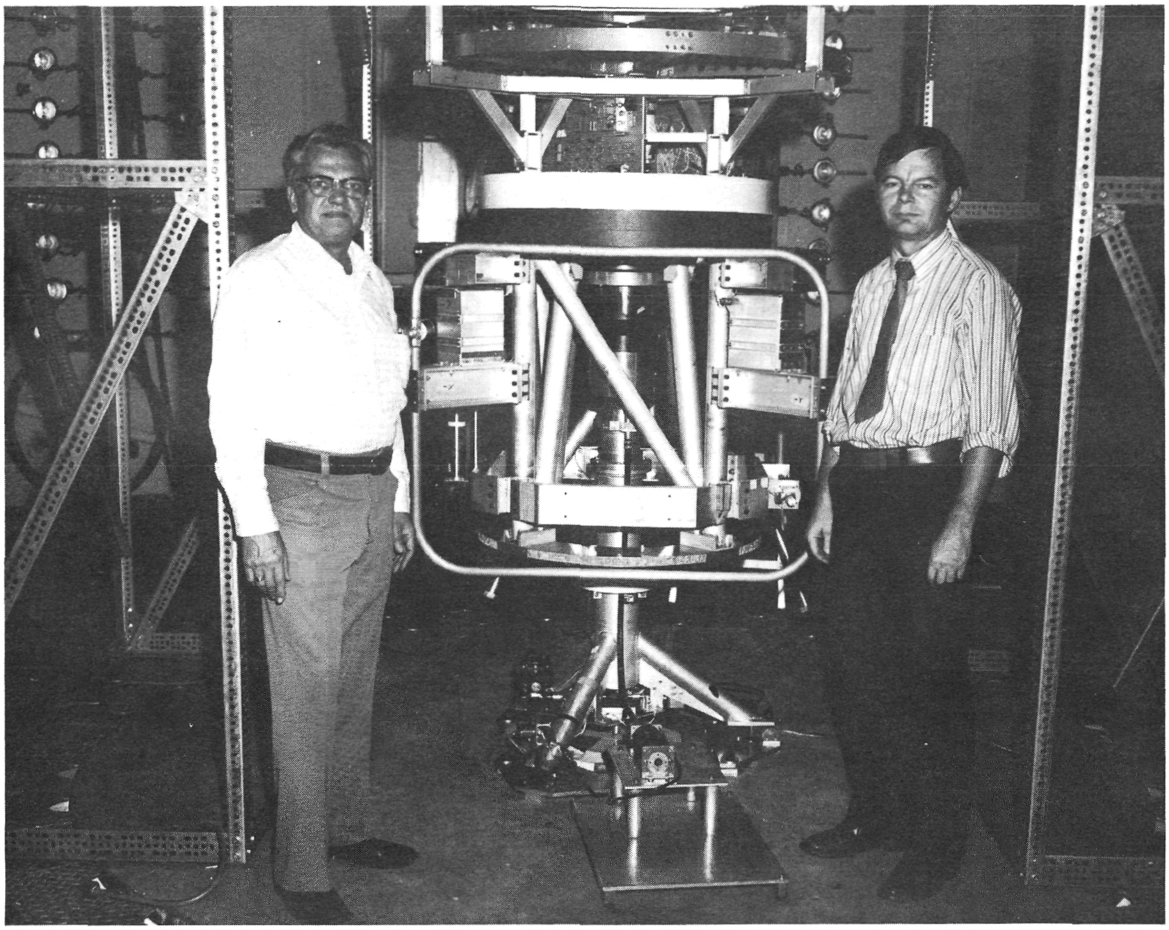

Figure 12. AE reaction wheel in vacuum chamber.

Table 3
Reaction-wheel Tests

Satellite	Wheel Diameter (cm)	Horiz Dist. from Vert. Axis (cm)	Vert Dist. from CG (cm)	Wheel Speed (rpm)	Weight (kg)	Spin Inertia (kg-m^2)	Inertia Ratio Transverse/ Spin
SAS-B	25.4	0	17.8	-	1.36	-	-
ITOS	76.2	0	58.4	115 150	9.1	50 87	0.8
AE	122	0	52.0	300 400	13.6	54	0.8

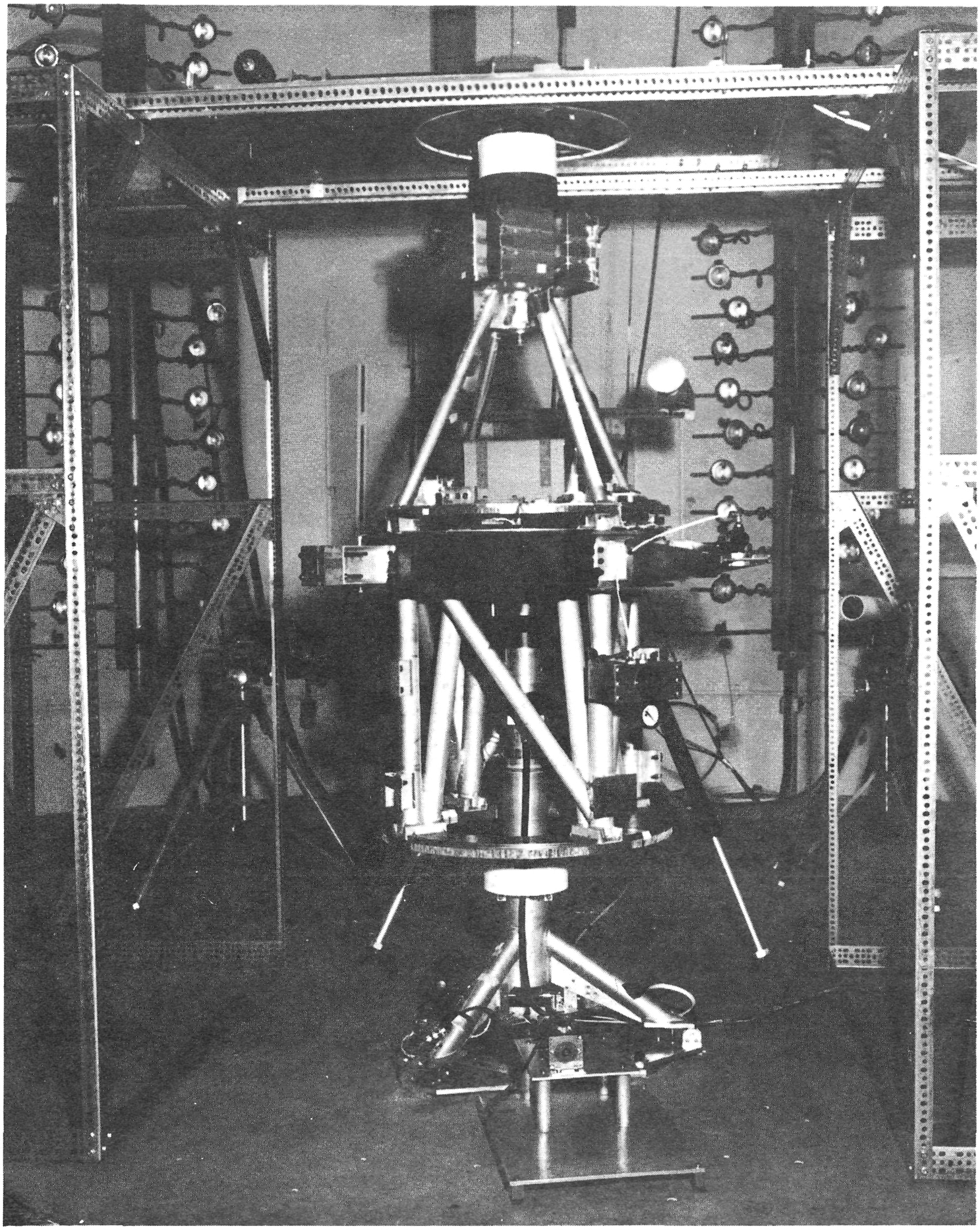

Figure 13. SMS active nutation damper in vacuum chamber.

were two-stage regulators that maintained an even output pressure as the input pressure dropped from 12.4 MPa (1800 psi) to 1.38 MPa (200 psi). An even output pressure was required to maintain an even thrust level during the test. The thrusters were mounted on 0.91-m (3-ft) arms opposite each other on the table. One was aimed up, the other was aimed down, complementing each other. The thrust level could be changed by altering the output pressure of the regulators.

To build up nutation, an oscillating motor and weight were mounted on the table. After table nutation had built up to an angle of 10° (cone angle), the motor was turned off and the nutation control system was turned on. Also, tests were run on the nutation control system with the nutation inducer on.

An active nutation damper (LAND) control system was tested for LAGEOS. The active damper is a cubical box (20 cm) containing a reaction wheel, angular accelerometer, and electronics. The box was mounted on a platform on the air-bearing table. A battery box for the LAND was mounted on the platform opposite the LAND. After nutation was built up on the table, the LAND box was turned on to reduce nutation.

The active nutation damper test data are given in table 4.

Table 4
Active Nutation Damper Tests

Satellite	Type System	Spin Inertia ($kg\text{-}m^2$)	Inertia Ratio Transverse/ Spin	Jet Torque (N-M)	Wheel Inertia ($kg\text{-}m^2$)
SMS	Jet	47	0.38	8	
LAGEOS LAND	Reaction wheel	28	0.18		0.003

Sequence of Events

The following list describes the procedure for setting up the equipment:

- Static balance table—a pendulous period $\geqslant$ 1 min.
- Dynamic balance—$<$ 0.002 $kg\text{-}m^2$ on the spin balance machine.
- Spin moment of inertia—measured to within 1 $kg\text{-}m^2$.
- Moment of inertia ratio—measured by comparing spin rate with nutation frequency.

A typical test would proceed as listed in the following sequence of events:

- 0800-0900–Battery charging, functional checkout, tank filling
- 0900-0910–Close chamber doors
- 0910-1200–Chamber pump down
- 1200-1600–Test operations
- 1600-1630–Vent chamber
- 1630-1730–Drain tanks for next day's test and change balance weight and/or moment of inertia ratios.

Typical test operations include a series of runs consisting of: (1) spinning the table to a desired speed; (2) retracting the bar and V-plate (see figure 14); (3) lowering the bell to release the table; (4) inducing the nutation (if required); (5) recording optron and accelerometer data; (6) capturing with bar and V-plate; and (7) raising the bell.

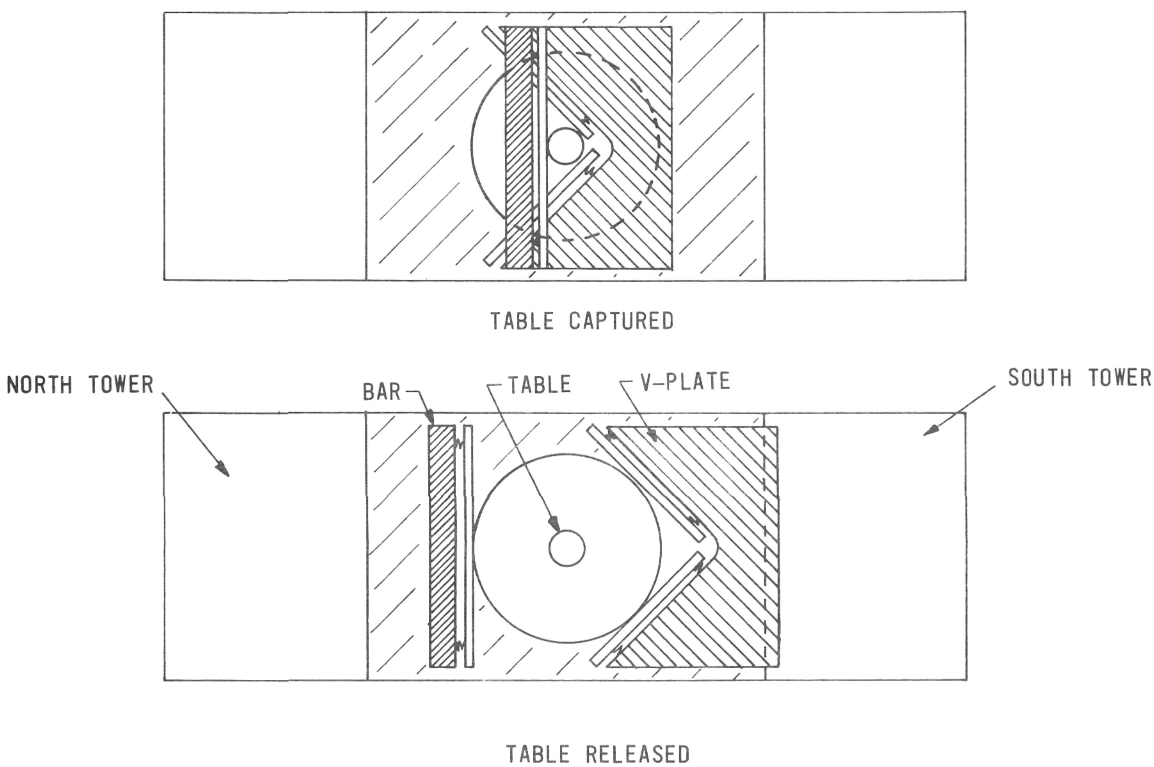

Figure 14. Overhead control mechanism (top view).

CONCLUSION

The air-bearing spin table has become a universal test facility for predicting energy dissipation on spinning spacecraft. Spacecraft components, such as fuel tanks, dampers, reaction wheels, and active nutation dampers, have been successfully tested. The results of these tests have been used, with excellent results, to predict spacecraft motion.

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Goddard Space Flight Center
National Aeronautics and Space Administration
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